Fusion dynamics of symmetric systems near barrier energies

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Abstract

The enhancement of the sub-barrier fusion cross sections was explained as the lowering of the dynamical fusion barriers within the framework of the improved isospin-dependent quantum molecular dynamics (ImIQMD) model. The numbers of nucleon transfer in the neck region are appreciably dependent on the incident energies, but strongly on the reaction systems. A comparison of the neck dynamics is performed for the symmetric reactions ^{58}Ni+^{58}Ni and ^{64}Ni+^{64}Ni at energies in the vicinity of the Coulomb barrier. An increase of the ratios of neutron to proton in the neck region at initial collision stage is observed and obvious for neutron-rich systems, which can reduce the interaction potential of two colliding nuclei. The distribution of the dynamical fusion barriers and the fusion excitation functions are calculated and compared them with the available experimental data.

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Heavy-ion fusion reactions at energies in the vicinity of the Coulomb barrier has been an important subject in nuclear physics for more than 20 years, which is involved in not only exploring several fundamental problems such as quantum tunneling in the multidimensional potential barrier etc, also investigating nuclear physics itself associated with nuclear structure, synthesis of superheavy nuclei etc [1]. The experimental fusion cross sections can be well reproduced by the various coupled channel methods, which include the couplings of the relative motion to the nuclear shape

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deformations, vibrations, rotations, and nucleon-transfer, such as CCFULL code [2]. However, the coupled channel models still have some difficulties in describing the fusion reactions for symmetric systems, especially for heavy combinations, in which the neck dynamics in the fusion process of two colliding nuclei plays an important role on the interaction potential, and consequently on the fusion cross section. Microscopic mechanism of the neck dynamics is significant for properly understanding the capture and fusion process in the formation of superheavy nuclei in massive fusion reactions [3]. The ImIQMD model has been successfully applied to treat heavy-ion fusion reactions near barrier energies in our previous works [4], in which the interaction potential energy is microscopically derived from the Skyrme energy-density functional besides the spin-orbit term and the shell correction is considered properly. In this letter, we will concentrate on exploring the influence of the dynamical mechanism in heavy-ion collisions near barrier energies on the fusion cross sections.

In the ImIQMD model, the time evolutions of the nucleons under the self-consistently generated mean-field are governed by Hamiltonian equations of motion, which are derived from the time dependent variational principle and read as

$$\dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}, \quad \dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i}. \tag{1}$$

The total Hamiltonian H consists of the kinetic energy, the effective interaction potential and the shell correction part as

$$H = T + U_{int} + U_{sh}. \tag{2}$$

The details of the three terms can be found in details in Ref. [4]. The shell correction term is important for magic nuclei induced fusion reactions, which constrains the fusion cross section in the sub-barrier region.

For the lighter reaction systems, the compound nucleus is formed after the two colliding nuclei is captured by the interaction potential. The quasi-fission reactions after passing over the barrier take place when the product Z_pZ_t of the charges of the projectile and target nuclei is larger than about 1600. In the ImIQMD model, the interaction potential $V(R)$ of two colliding nuclei as a function of the distance R between their centers is defined as [5]

$$V(R) = E_{pt}(R) - E_p - E_t. \tag{3}$$

Here the E_{pt}, E_p and E_t are the total energies of the whole system, projectile and target, respectively. The total energy is the sum of the kinetic energy, the effective potential energy and the shell correction energy. In the calculation, the Thomas-Fermi approximation is adopted for

evaluating the kinetic energy. Shown in in Fig. 1 is a comparison of the various static interaction potentials, such as Bass potential [6], double-folding potential used in dinuclear system model [3], proximity potential of Myers and Swiatecki [7], the adiabatic barrier as mentioned in Ref. [8] and ImIQMD static and dynamical interaction potentials for head on collisions of the reaction system ^{58}Ni+^{58}Ni. It should be noted that the potentials calculated by the ImIQMD model have included the shell effects that evolve from the projectile and target nuclei into the composite system. The contribution of the shell correction energy to the interaction potential is shown separately in the right panel of the figure at frozen densities and different incident energies. The static interaction potential means that the density distribution of projectile and target is always assumed to be the same as that at initial time, which is a diabatic process and depends on the collision orientations and the mass asymmetry of the reaction systems. The corresponding barrier heights are indicated for the various cases. However, for a realistic heavy-ion collision, the density distribution of the whole system will evolve with the reaction time, which is dependent on the incident energy and impact parameter of the reaction system [9]. In the calculation of the dynamical potentials, we only pay attention to the fusion events, which give the dynamical fusion barrier. At the same time, a stochastic rotation is performed for each simulation event. One can see that the heights of the dynamical barriers are reduced gradually with decreasing the incident energy, which result from the reorganization of the density distribution of two colliding nuclei due to the influence of the effective interaction potential on each nucleon. The dynamical barrier with incident energy $E_{c.m.}$=105 MeV approaches the static one. The lowering of the dynamical fusion barrier is in favor of the enhancement of the sub-barrier fusion cross sections, which can give a little information that the cold fusion reactions are also suitable to produce superheavy nuclei although an extra-push energy is needed for heavy reaction systems [10]. The energy dependence of the nucleus-nucleus interaction potential in heavy-ion fusion reactions was also investigated by the time dependent Hartree-Fock theory and the lowering of dynamical barrier near Coulomb energies was also observed [11].

The influence of the structure quantities such as excitation energies, deformation parameters of the collective motion can be embodied by comparing the fusion barrier distributions calculated from the coupled channel models and the measured fusion excitation functions. In the ImIQMD model, the dynamical fusion barrier is calculated by averaging the fusion events at a given incident energy and a fixed impact parameter. To explore more information on the fusion dynamics, we also investigate the distribution of the dynamical fusion barrier, which counts the dynamical barrier per fusion event and satisfies the condition $\int f(B_{fus})dB_{fus} = 1$. Fig. 2 shows the barrier

distribution for head on collisions of the reaction ^{58}Ni+^{58}Ni at the center of mass incident energies 96 MeV and 100 MeV, respectively, which correspond to below and above the static barrier $V_b = 97.32$ MeV as labeled in Fig. 1, and a comparison with the neutron-rich system ^{64}Ni+^{64}Ni. The distribution trend moves towards the low-barrier region with decreasing the incident energy, which can be explained from the slow evolution of the colliding system. The system has enough time to exchange and reorganize nucleons of the reaction partners at lower incident energies. A number of fusion events are located at the sub-barrier region, which is favorable to enhance sub-barrier fusion cross sections. There is a little distribution probability that the fusion barrier is higher than the incident energy 96 MeV owing to dynamical evolution of two touching nuclei. We should note that the fusion events decrease dramatically with incident energy in the sub-barrier region. Neutron-rich system has the distribution towards the low-barrier region owing to the lower dynamical fusion barrier, which favors the enhancement of the fusion cross section.

The neck formation in heavy-ion collisions close to the Coulomb barrier is of importance for understanding the enhancement of the sub-barrier cross sections. A phenomenological approach (neck formation fusion model) was proposed by Vorkapić [12] to fit experimental data that can not be reproduced properly by the coupled channel models. Using a classical dynamical model Aguiar, Canto, and Donangelo have pointed out that the neck formation in heavy-ion fusion reactions may explain the lowering of the barrier [13]. Using the ImIQMD model, we carefully investigate the dynamics of the formation of the neck in heavy-ion fusion reactions. The neck region is defined as a cylindrical shape along the collision orientation with the high 4 fm when the density at the touching point reaches $0.02\rho_0$. Shown in Fig. 3 is the numbers of nucleon transfer from projectile to target in the neck region at incident energies 95 MeV and 100 MeV in the left panel and a comparison of the system ^{58}Ni+^{58}Ni and ^{64}Ni+^{64}Ni in the right panel. The evolution time starts at the stage of the neck formation. A slight peak appears for both cases because the dynamical fluctuation takes place in the formation process of the neck. Larger numbers of neutron transfer are obvious especially for neutron-rich system, which can be easily understood because the neutron transfer does not affected by the repulsive Coulomb force. The transfer of protons reduces the interaction potential of two colliding nuclei. The time evolution of the ratio of neutron to proton in the neck region and the radius of the neck at incident energy 100 MeV are also calculated as shown in Fig. 4 for the reactions ^{58}Ni+^{58}Ni and ^{64}Ni+^{64}Ni. It is clear that the neutron-rich system has the larger values of the N/Z ratio and the neck radius. An obvious bump in the evolution of the N/Z ratio appears at the initial stage of the formation of the neck for both systems due to the Coulomb repulsion for protons.

In the ImIQMD model, the fusion cross section is calculated by the formula [4]

$$\sigma_{fus}(E) = 2\pi \int_0^{b_{max}} bp_{fus}(E,b)db = 2\pi \sum_{b=\Delta b}^{b_{max}} bp_{fus}(E,b)\Delta b, \tag{4}$$

where $p_{fus}(E,b)$ stands for the fusion probability and is given by the ratio of the fusion events N_{fus} to the total events N_{tot}. In the calculation, the step of the impact parameter is set to be $\Delta b = 0.5$ fm. In Fig. 5 we show a comparison of the calculated fusion excitation functions and the well-known one dimensional Hill-Wheeler formula [14] as well as the experimental data for the reactions ^{58}Ni+^{58}Ni [15] and ^{64}Ni+^{64}Ni [16]. One can see that a strong enhancement of the fusion cross sections for the neutron-rich combination ^{64}Ni+^{64}Ni is obvious, especially in the sub-barrier region. The Hill-Wheeler formula reproduces rather well the fusion cross sections at above barrier energies, but underestimate obviously the sub-barrier cross sections. The ImIQMD model reproduces the experimental data rather well over the whole range. In the piont of view from dynamical calculations, the reorganization of the density distribution of the colliding system results in the lowering of the dynamical fusion barrier, which consequently enhances the sub-barrier fusion cross sections. The phenomenon is more clearly for neutron-rich combinations.

In conclusion, using the ImIQMD model, the fusion dynamics in heavy-ion collisions in the vicinity of the Coulomb barrier is investigated systematically. The dynamical fusion barrier is reduced with decreasing the incident energies, which results in the enhancement of the sub-barrier fusion cross sections. The distribution forms of the dynamical fusion barrier are dependent on the incident energies and the N/Z ratios in the neck region of the reaction systems. The nucleon transfer in the neck region reduces the interaction potential of two colliding nuclei. The lower fusion barrier is in favor of the enhancement of the fusion cross sections of the neutron-rich systems.

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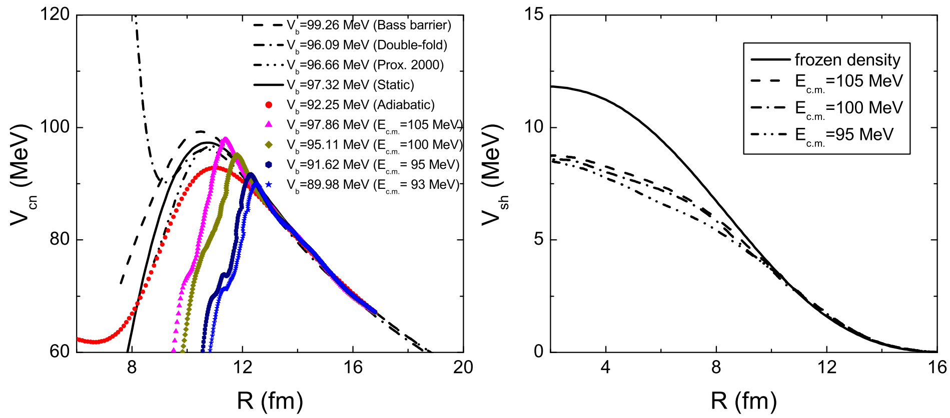

Figure 1: Comparisons of the reaction ^{58}Ni+^{58}Ni for various static interaction potentials (Bass, double-folding, proximity and ImIQMD potential at frozen density), the dynamical fusion potentials at different incident energies and the adiabatic potential in Ref. [8] (left panel), and the contributions of the shell corrections calculated at the frozen densities and at incident energies 95 MeV, 100 MeV and 105 MeV, respectively.

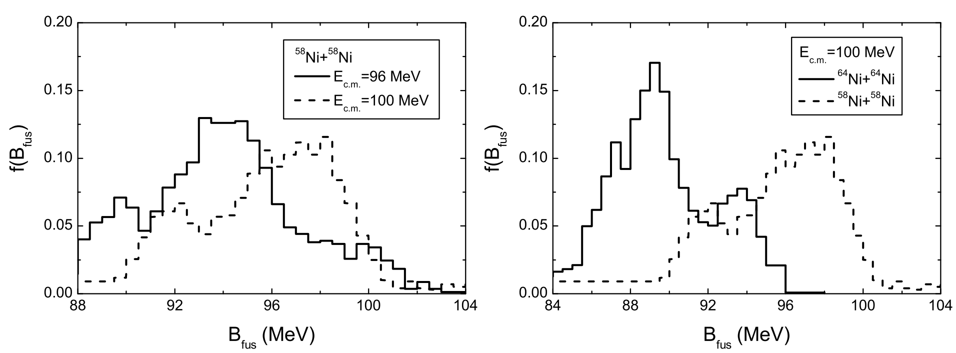

Figure 2: Distribution of the dynamical fusion barriers at incident energies 96 MeV and 100 MeV in the center of mass frame (left panel) and comparison of the systems ^{58}Ni+^{58}Ni and ^{64}Ni+^{64}Ni (right panel).

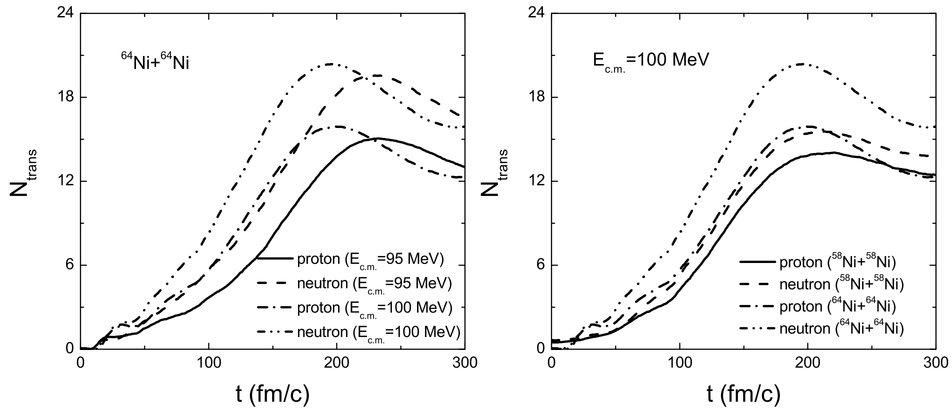

Figure 3: Nucleon transfer from projectile to target nucleus in the neck region at different incident energies (left panel) and for systems ^{58}Ni+^{58}Ni and ^{64}Ni+^{64}Ni (right panel).

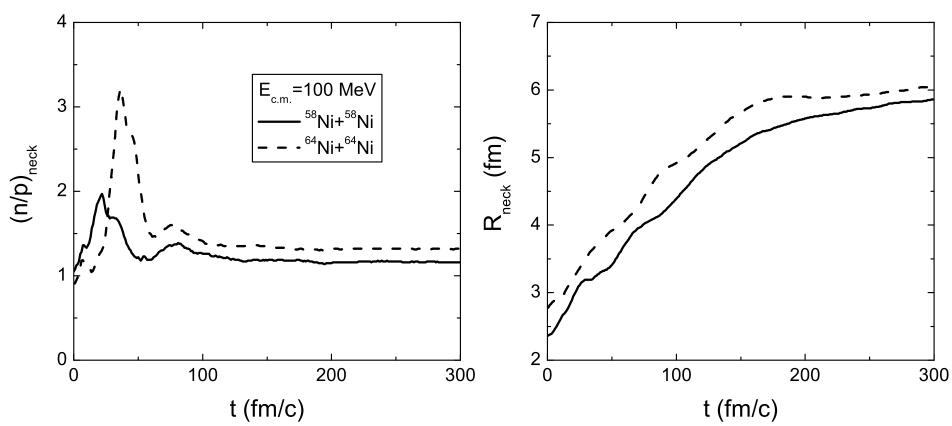

Figure 4: The ratio of neutron to proton in the neck region (left panel) and the radius of the neck (right panel) as functions of the evolution time at incident energy 100 MeV.

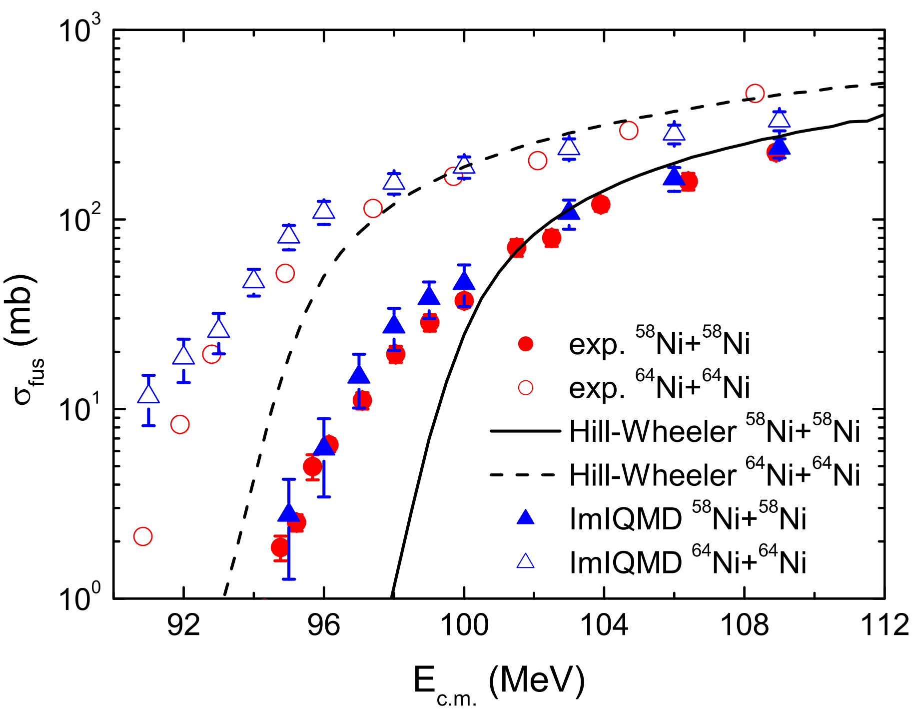

Figure 5: The calculated fusion excitation functions for the reactions ^{58}Ni+^{58}Ni and ^{64}Ni+^{64}Ni, and compared them with the Hill-Wheeler formula [14] and the experimental data [15, 16].